

## ARCHITECTURE FOR LARGE OPTICAL FIBER ARRAY USING STANDARD $1 \times 2$ COUPLERS

### Related Applications

The present application is a continuation of U.S. Patent Application No.  
5 09/107,399 filed on June 30, 1998, which claims priority from U.S. Provisional  
Application No. 60/090,817 filed on June 26, 1998.

### Background of the Invention

#### Field of the Invention

The present invention relates generally to sensor arrays for acoustic sensing  
10 systems, and more specifically, to sensor arrays in which differences in the returned  
optical power are reduced.

#### Description of the Related Art

Arrays of fiber optic interferometric sensors show promise in applications where  
size, electrical interference, and electromagnetic detection make electronic sensors  
15 impractical. Such interferometric sensors are capable of measuring a parameter (i.e., a  
measurand) with a very high dynamic range (e.g., 120 dB). Optical sensor arrays are  
formed by connecting a series of sensors using fiber optic lines. If each sensor in an  
array requires a dedicated fiber to carry the detection signal, the large number of fibers  
required quickly becomes unwieldy as the number of sensors increases.

20 Optical couplers are commonly used to couple optical signals from a distribution  
bus to the sensors, and from the sensors to a return bus. In an array in which amplifiers  
are not used to periodically boost the signal strength, delivering sufficient optical signal  
to each of the sensors can be problematic. In addition, there may be significant variations  
in the optical power levels returned to the detectors, thereby complicating the signal  
25 processing.

Although significant progress has been made in recent years with respect to the  
sophistication of sensor array configurations and signal processing techniques, there is  
still need for improved architectures based on standardized components such as  $1 \times 2$

couplers, in which the returned optical signals have respective powers within a relatively narrow range.

### Summary of the Invention

One embodiment of the invention is a method of multiplexing optical signals for  
5 a sensor array. The method includes the steps of providing a first plurality of sensors having respective inputs and outputs, connecting a first plurality of input couplers to the inputs of the sensors, connecting the input couplers to respective distribution fiber lines which carry respective optical signals having different carrier frequencies, connecting a first plurality of output couplers to the outputs of the sensors, connecting the output  
10 couplers to a first return fiber line, and selecting coupling ratios of the output couplers to reduce differences in returned optical signal power levels.

Another embodiment of the invention is a method of multiplexing optical signals for a sensor array. The method includes the steps of providing a plurality of sensors having respective inputs and outputs (in which the inputs and outputs are connected to  
15 respective input and output couplers), providing distribution fiber lines which carry respective optical signals having different carrier frequencies, connecting the input couplers to the distribution fiber lines so that each distribution fiber line is only coupled to sensors that are non-adjacent, connecting the output couplers to at least two return fiber lines so that each return line is only coupled to sensors that are non-adjacent, and  
20 selecting the coupling ratios of the input and output couplers to reduce differences in the returned optical signal power levels.

A further embodiment of the invention is a sensor array that includes distribution fiber lines, return fiber lines, and sensor groups. Each of the sensor groups in turn comprises sensors, input couplers, and output couplers. The input couplers and the  
25 output couplers are connected to respective sensors, in which each of the input couplers within any one of the sensor groups is connected to a different one of the distribution fiber lines. Further, each of the return fiber lines is connected to all output couplers within respective ones of the sensor groups. The coupling ratios of the input couplers and the output couplers in the signal array are chosen to reduce differences in the  
30 returned optical signal power levels. In a preferred embodiment, this apparatus is an

m × n sensor array comprising m distribution fiber lines, n return fiber lines, and n sensor groups.

A further embodiment of the invention is a sensor array that includes distribution fiber lines and sensor groups. Each of the sensor groups comprises sensors, input couplers, output couplers, and return fiber lines. The input couplers and the output couplers are connected to respective ones of the sensors, wherein no more than two of the input couplers within any one of the sensor groups are connected to any one of the distribution fiber lines. Further, the distribution fiber lines are only coupled to sensors that are non-adjacent. The return fiber lines are connected to each of the output couplers, such that each of the return fiber lines is only coupled to sensors that are non-adjacent. Also, the coupling ratios of the input couplers and the output couplers in this signal array are chosen to reduce differences in the returned optical signal power levels. In a preferred embodiment, this apparatus is a sensor array containing m distribution fiber lines and n sensor groups, in which each of the n sensor groups each contains 2m sensors.

#### Brief Description of the Drawings

FIGURE 1 is a schematic of one embodiment of the invention in which optical signals from a plurality of lasers pass through downleads, into sensors, and are returned to a plurality of detectors for processing.

FIGURE 2, comprising FIGURES 2A-2H, illustrates one implementation of the embodiment of FIGURE 1, specifically, a 6 × 16 array including 16 sensor groups, in which each sensor group has a dedicated return fiber line (bus).

FIGURE 3 illustrates the returned optical power versus sensor number for the embodiment shown in FIGURE 2.

FIGURE 4, comprising FIGURES 4A-4H, illustrates another implementation of the embodiment of FIGURE 1, specifically a 6 × 16 array including 8 sensor groups, in which each sensor group has two return fiber lines, and no two adjacent sensors in the array have either a common distribution fiber line or a common return fiber line.

FIGURE 5 illustrates the returned optical power versus sensor number for the embodiment shown in FIGURE 4.

### Detailed Description of the Preferred Embodiment

One embodiment of an acoustic sensing system 100 in accordance with the present invention is shown in FIGURE 1. A plurality of lasers L1, L2, L3, L4, L5, L6 generate respective optical signals of different optical frequencies which are modulated by respective modulators M1, M2, M3, M4, M5, M6. In one preferred embodiment of the invention, the lasers L1-L6 generate optical radiation at a nominal wavelength of 1319 nanometers (nm), corresponding to an optical frequency of approximately 230 THz in optical fiber. The frequencies are preferably separated by approximately 1 GHz and are modulated by respective carriers at approximately 3 MHz, with each of the carrier frequencies being unique so that return signals can be multiplexed on the same return fiber before being processed. The lasers L1-L6 may advantageously be Nd:YAG lasers which are all identical except for the optical frequency at which they are operated. The temperatures of the lasers L1-L6 are preferably adjusted so that each laser has a unique operating optical frequency to avoid optical interference between the laser signals.

The optical signals propagate along respective optical feed lines F1-F6 which are connected to an optical connecting block 140. Distribution fiber lines DF1-DF6 (FIGURE 2) are connected to the feed lines F1-F6 within the optical connecting block 140. The optical signals from the sensors travel through the distribution fiber lines DF1-DF6 towards a plurality of sensors, which in the exemplary embodiment of FIGURE 1 total 96 and are designated S1-S96. The optical signals S1-S96 pass through return optical fibers RF1-RF16 (FIGURE 2). The returned optical signals then pass through the connecting block 140 and return fiber lines R101-R116 to respective optical detectors D1-D16. The returned optical signals are detected by the detectors D1-D16 which are coupled to processing electronics 200. The optical distribution fibers DF1-DF6, return fibers RF1-RF16, and the sensors S1-S96 are preferably housed within a cable 210 to protect these components against the environment.

One preferred embodiment of the invention shown in FIGURE 1 is illustrated in FIGURES 2 and 2A-2H. In this embodiment, the sensors S1-S96 are divided into 16 sensor groups of 6 sensors each. A first sensor group 301 is shown in FIGURE 2A. The sensor group 301 is optically closest to the lasers L1-L6 and to the processing electronics 200. The first sensor group 301 is coupled to the six distribution fiber lines DF1-DF6

through which the input optical signals are carried. The distribution fiber lines DF1-DF6 are connected to respective standard  $1 \times 2$  input couplers 320 which in turn are connected to sensors S1-S6. The input couplers 320 couple a fraction of the input signal to their respective sensors S1-S6 and pass the remaining optical signal onto other couplers 320, although for some applications the first sensor group 300 alone (without additional sensor groups) may be utilized, in which case the coupling ratio for each of the input couplers 320 is 100%. In the embodiment shown in FIGURE 2, however, the coupling ratio for the input couplers 320 of the first sensor group 300 is selected to be 3.5%, with the remaining fraction (96.5% minus any excess losses) of the input signals propagating towards the other sensor groups.

The optical signals passing through the sensors S1-S96 are altered by the sensors (which may be Mach-Zehnder interferometers) to contain information which can then be extracted by the processing electronics 200. For example, in exemplary embodiments, the sensors S1-S96 are responsive to impinging acoustic signals to vary the phase of optical radiation passing through the sensors S1-S96. After passing through the sensors S1-S6, the information-carrying optical signals corresponding to the first five distribution fibers DF1-DF5 (i.e., from the sensors S1-S5) pass through respective standard  $1 \times 2$  output couplers 330 to a return fiber line RF1, and then to the detector D1 via the return line R101 (FIGURE 1). The optical signal corresponding to the sixth distribution fiber DF6, which passes through the sensor S6, may enter the return fiber line RF1 directly without an output coupler. However, the optical signal from the sixth sensor S6 does pass through the five optical couplers 330 corresponding to the sensors S1-S5 as it propagates through the return fiber RF1. Similarly, the optical signal from the fifth sensor S5 passes through the four couplers 330 associated with the sensors S1-S4, and so on. The output couplers 330 of the other sensor groups have a similar configuration with respect to the return fiber lines RF1-RF16.

The output couplers 330 have respective coupling ratios chosen to reduce differences in the respective returned optical signal power levels. The coupling ratios are preferably chosen such that the signal levels of the optical signals returned from the sensor groups to their associated detectors D1-D16 are within a 7 dB range of each other. Thus, the respective coupling ratios for the output couplers 330 within each sensor group

are selected to be approximately 1/2, 1/3, 1/4, 1/5, and 1/6. In one preferred working embodiment, the output coupling ratios were chosen to be about 47, 30, 25, 20 and 15%, respectively, as illustrated in FIGURE 2A. These coupling ratios deviate from the ideal ratios expressed above to compensate for excess losses in the return lines. In particular, the coupling ratios of the return couplers 330 are selected to be progressively larger from the sensor S1 to the sensor S6 (S6 has an effective coupling ratio of 100%) to compensate for the fact that the signals from the sensors S1-S6 pass through different combinations of couplers, causing each return signal to have a different overall transmission through the return fiber RF1.

In the embodiment of FIGURE 2, additional sensor groups are coupled to the same distribution fiber lines DF1-DF6 to which the first sensor group 301 is coupled. The return fiber line RF1, RF2, ..., RF16 for each sensor group is unique, however. That is, the sensors from different sensor groups do not share a return fiber line. Thus, each of the return fiber lines RF1-RF16 is dedicated to a particular sensor group, with the optical signals from each sensor group being multiplexed onto one return fiber line.

In each sensor group, a certain fraction of the input optical signal in each distribution fiber line DF1-DF6 is directed (coupled) into the sensors of that group. However, to maintain roughly the same level of input optical power at each sensor, this fraction is higher for sensor groups further removed from the lasers L1-L6, since optical power must be shared among fewer subsequent sensor groups. Thus, the input coupling ratio is chosen to be 7% at sensors S31-S54, 11% at sensors S55-S66, 15% at sensors S67-S72, 20% at sensors S73-S78, 30% at sensors S79-S84, 47% at sensors S85-S90, and 100% at sensors S91-S96 at which point an input coupler is no longer needed.

The coupling ratios of the input couplers 320 and the output couplers 330 are selected to reduce differences in the level of optical signal delivered to each sensor S1-S96, and more particularly, to reduce differences in the returned optical signal power levels at the detectors D1-D16. Preferably, the 96 optical signals arriving at the detectors D1-D16 have respective powers within a 7 dB range, as illustrated graphically in FIGURE 3.

Note that in FIGURE 3, the return power within each group varies with respect to the positions of the sensors in each group because of the five different return coupling

ratios of the couplers 330 in each group. The return power is progressively reduced for the groups 302, 303, 304, and 305, because the same input coupling ratio is retained, but each group receives progressively less input power from the respective distribution lines. The group 306 has a large return power because of the increase of the input coupling ratio to 7%. The subsequent groups 307, 308, and 309 having 7% input coupling ratios have progressively less return power. The changes in return power for the groups 310-316 can likewise be explained by their respective input coupling ratios in view of the lower power remaining on the distribution lines at the inputs to each group. Small changes to the coupling ratios which would exactly equalize the returned signal powers are foregone in order to reduce the number of unique coupling ratios employed. This approach reduces the manufacturing costs of the array while still providing substantially equal returned optical signals, i.e., within a 7 dB range.

FIGURE 3 illustrates the returned optical power at the detectors D1-D16 corresponding to each sensor number for the embodiment of FIGURE 2. The returned optical power (dBm) for an optical power of 15.44 dBm (35 mW) from each laser L1-L6 was calculated by making certain assumptions about the optical losses for this configuration. Specifically, the optical losses were assumed to be 0.15 dB for each splice (designated as an "x" in FIGURE 2), 3.5 dB at each modulator M1-M6, 0.5 dB for each input connector 320 and each output connector 330, 0.5 dB for the connecting block 140, 6.8 dB at each sensor S1-S96, 5 dB at each detector D1-D16, and 0.5 dB per kilometer (km) of fiber. Also, the length of the download portion shown in FIGURE 1 was taken to be 1.2 km, and the spacing between adjacent sensors was taken to be 0.05 km (50 meters). Further, the respective total losses for the various optical paths between the lasers L1-L6 and the detectors D1-D16 (96 paths in all, in which each path is associated with one of the sensors S1-S96) was calculated by taking into account losses common to all of the optical paths. Specifically, there was assumed to be one splice (not shown) between each of the lasers L1-L6 and their respective modulators M1-M6, one splice (not shown) between each of the modulators and the connecting block 140, one splice on either side of each of the optical connectors 320 (330), one splice on each side of each sensor S1-S96, and one splice (not shown) between the optical connecting block and each of the detectors D1-D16. As illustrated in FIGURE 3, the returned optical powers

collectively fall within about a 5 dB range, although a wider range up to 6 or 7 dB may also be provided.

Another preferred embodiment of the invention shown in FIGURE 1 is illustrated in FIGURE 4. The embodiment of FIGURE 4 includes 8 sensor groups of 12 sensors each. The sensors within each group are coupled (using output couplers 330) to two return fiber lines so that adjacent sensors are not coupled to the same return fiber line. For example, a first sensor group 401, return fibers RF1 and RF2 are coupled to the odd and even numbered sensors in that group, respectively. Thus, if either the return fiber RF1 or RF2 breaks, information from every other sensor is lost, but it is still possible to extract useful information from the sensor group 400. This would not be possible in a group in which every sensor were tied to the same return fiber line.

Another feature of the embodiment of FIGURE 4 is that each of the 6 distribution fiber lines D1-D6 is coupled to two sensors within each sensor group (using input couplers 320), but the coupling geometry is staggered such that a given optical signal from one of the lasers L1-L6 does not serve as input to two sensors coupled to the same return fiber line. Otherwise, optical signals on the respective return lines RF1-RF6 could not be multiplexed.

The other sensor groups 402-408 are likewise tied to the six distribution fiber lines D1-D6, such that no two adjacent sensors in the array are served by the same distribution fiber line. Each sensor group, however, has two return fiber lines dedicated to its sensors, with no two adjacent sensors being tied to the same return fiber line. Thus, the sensor array of FIGURE 4 is constructed such that the breakage of one of the fiber lines (either one of the distribution fiber lines DF1-DF6 or one of the return fiber lines RF1-RF16) will not affect any two adjacent sensors. In this way, useful information can still be extracted from each of the sensor groups. Further, the returned optical signals of this embodiment also preferably have respective powers within a 6-7 dB range, and more preferably 5 dB, after passing through the return fiber lines RF1-RF16 and being detected by the detectors D1-D16.

FIGURE 5 illustrates the returned optical power at the detectors D1-D16 corresponding to each sensor number for the embodiment of FIGURE 4 and is analogous to FIGURE 3. Similar assumptions regarding optical losses made for FIGURE 3 were



also made for FIGURE 5, and, once again, an optical power of 15.44 dBm (35 mW) was assumed for each laser L1-L6. As illustrated in FIGURE 5, the returned optical powers collectively fall within about a 5 dB range, although a wider range up to 6 or 7 dB may also be provided.

- 5           The invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is therefore indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be
- 10   embraced within that scope.